Dark Matter Theory

(Trying to solve a 78 year-old mystery…)

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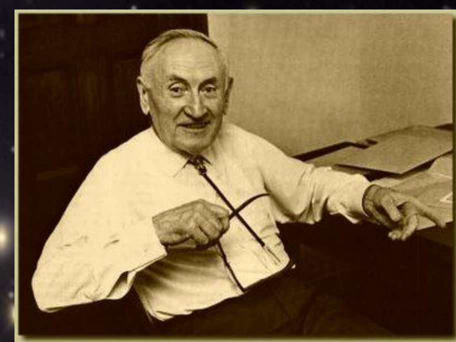
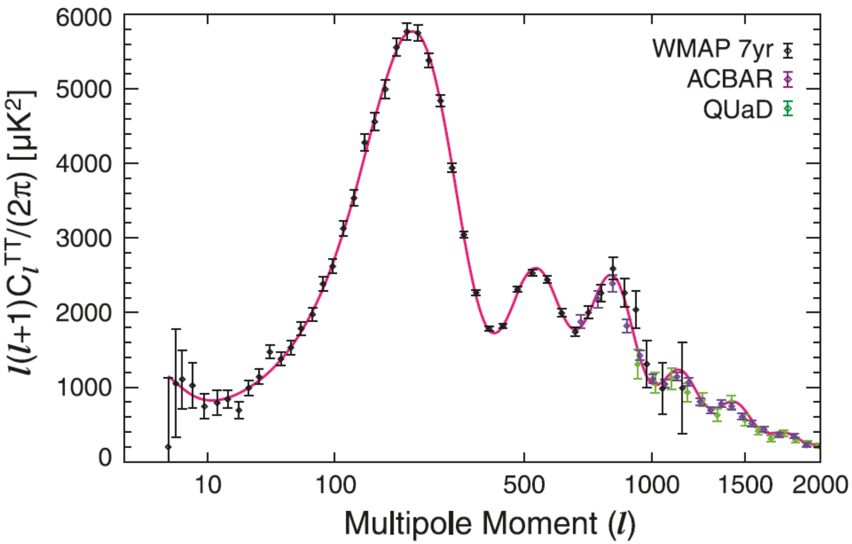
Invited talk at EPS-HEP conference, Grenoble, July 26, 2011

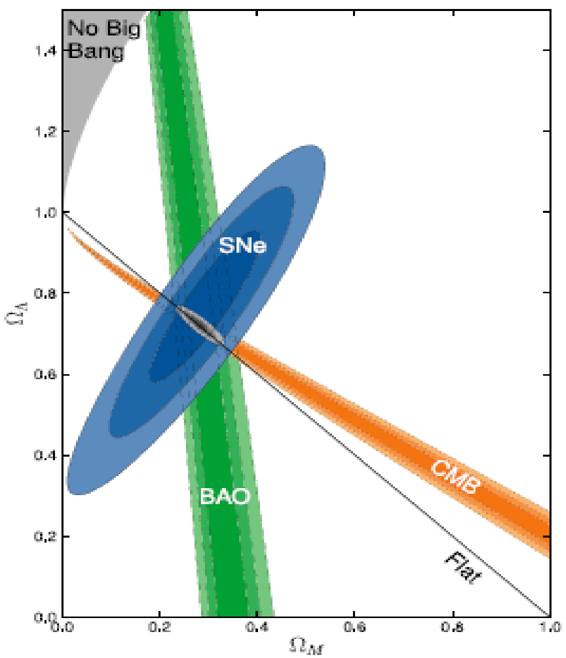


Fritz Zwicky, 1933: "If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter."

Coma galaxy cluster



E. Komatsu et al. (WMAP team) , 2010



R. Amanullah et al. (SCP Collaboration), 2010

WMAP 2010:

$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.003 \pm 0.01$$

$$\Omega_{\Lambda} = 0.727 \pm 0.030 \qquad \boxed{\Omega_{CDM} h^2 = 0.1120 \pm 0.0056}$$

$$\Omega_{B} = 0.0455 \pm 0.0028 \qquad h = 0.704 \pm 0.025$$

The ΛCDM Model:

Cold Dark Matter model (meaning electrically neutral particles moving non-relativistically, i.e., slowly, when structure formed) with a cosmological constant Λ being the dark energy.

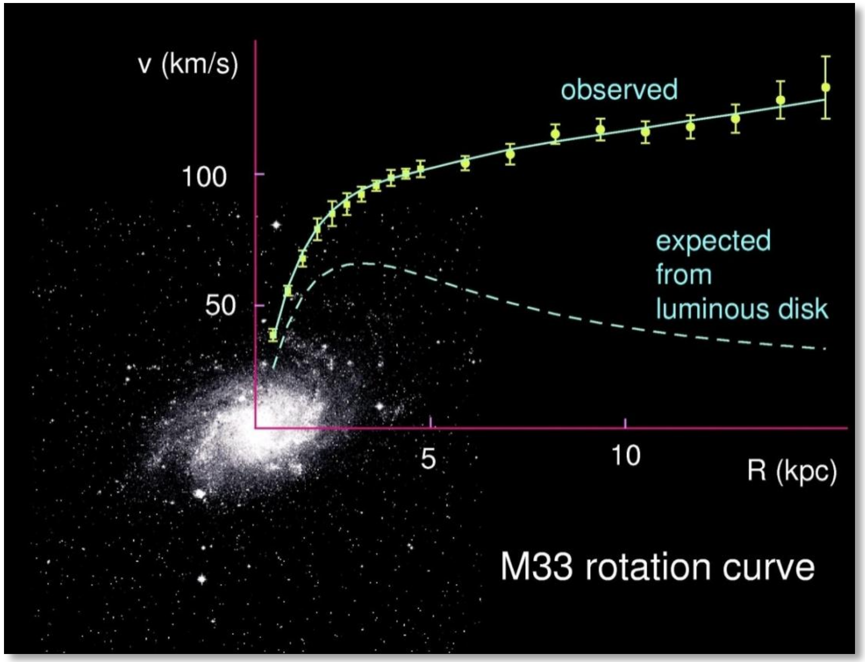
Ω_{CDM} h^2 = 0.11

Seems to fit all cosmological data!

Note: "Dark Matter" was coined by Zwicky; maybe "Invisible Matter" would have been a better name…

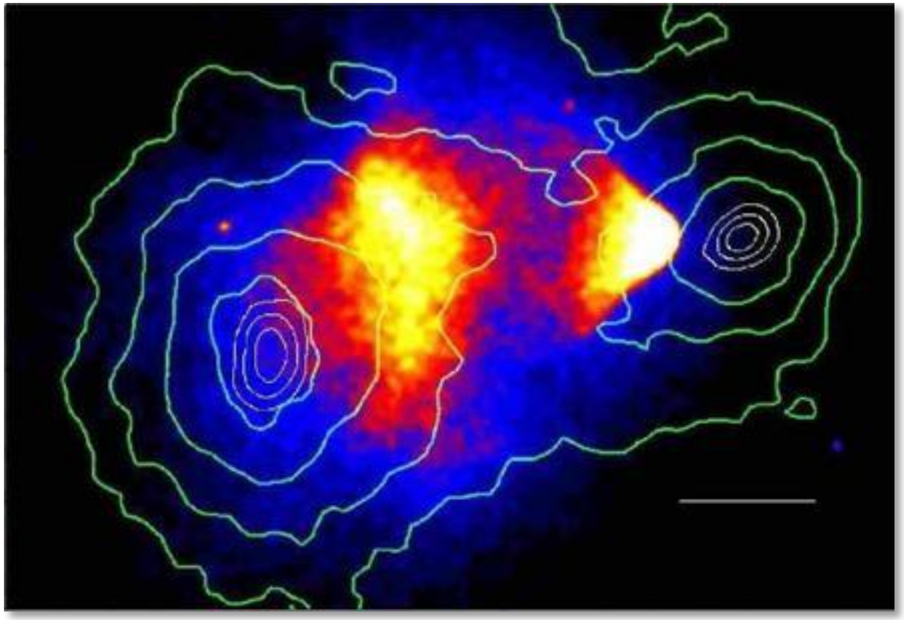
Dark matter needed on all scales!
$\Rightarrow$ Modified Newtonian Dynamics (MOND) and other *ad hoc* attemps to modify Einstein's or Newton's theory of gravitation do not seem plausible

Galaxy rotation curves



L.B., Rep. Prog. Phys. 2000

Colliding galaxy clusters

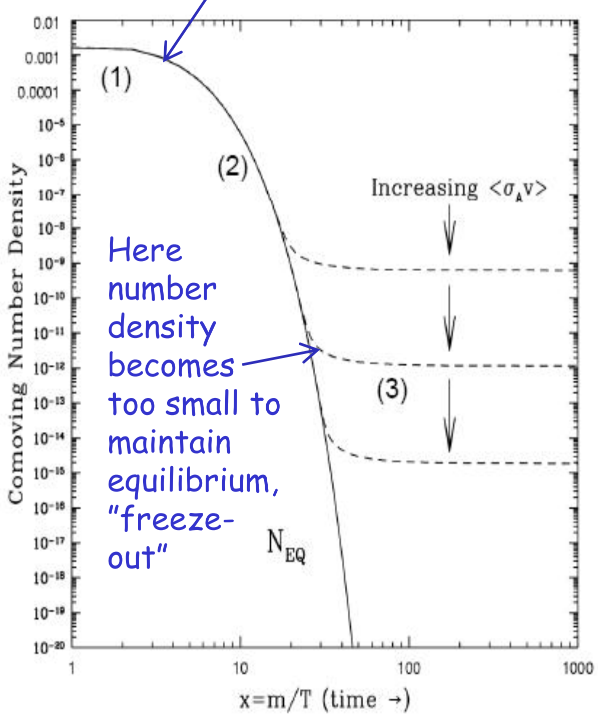


The bullet cluster, D. Clowe et al., 2006

(*cf.* new colliding cluster,Abell 2744, J. Marten et al., 2011)

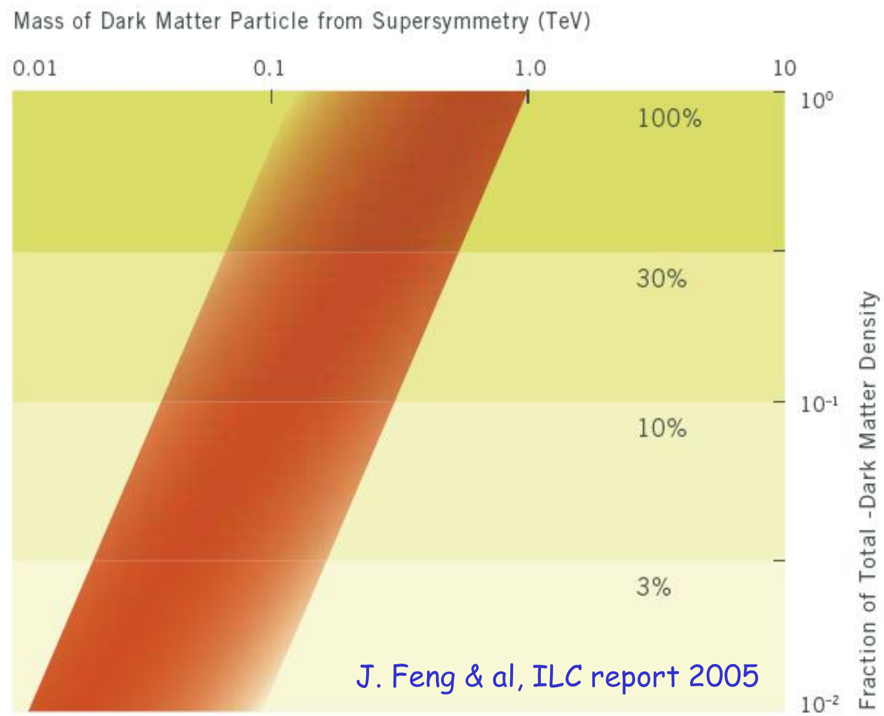
The particle physics connection: The "Weakly Interacting Massive Particle (WIMP) miracle". Is the CDM particle a WIMP?

Equilibirium curve for thermal production in the early universe. Here temperature was greater than $2Mc^2$, so the particles were in thermal equilibrium.



For thermal production, $\frac{\Omega_{WIMP}h^2}{0.11} \cong \frac{3\cdot 10^{-27}\ cm^3 s^{-1}}{\langle \sigma v \rangle}$

For typical gauge couplings, and the weak interaction mass scale, 100 – 1000 GeV, for the DM particle, the observed relic density appears without fine-tuning. Example, supersymmetry:



J. Feng & al, ILC report 2005

Other interesting WIMPs: Lightest Kaluza-Klein particle, Inert Higgs doublet,...

There have been very many clever ideas relating to WIMPs appearing during the last few years:

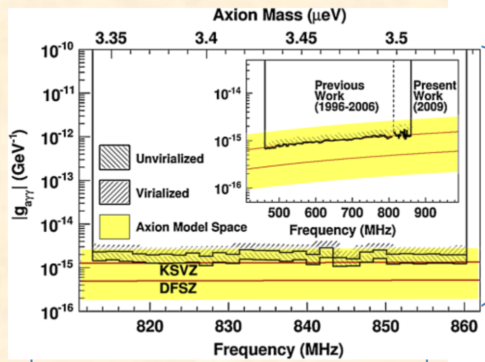
- Dark stars (D. Spolyar, K. Freese and P. Gondolo, 2008; F. Iocco, 2008; Sandick, 2010; S. Sivertsson and P. Gondolo, 2010; P. Scott et al., 2011;…) may have been powered by DM annihilation giving large-mass stars with unusual properties.
- Inelastic dark matter (D. Tucker-Smith and N. Weiner, 2001, 2005; J. March-Russell, C. McCabe and M. McCullough, 2008; D. Finkbeiner, T. Lin and N. Weiner, 2009; D.S.M. Alves et al., 2010;…) may have enhanced detection rates due to transition to excited states.
- Dynamical DM (K. Dienes and B. Thomas, 2011) – multicomponent model with very many different contributions to DM.
- Leptophilic DM (P.J. Fox and E. Poppitz, 2009; B. Kyae, 2009; D. Spolyar et al., 2009; A. Ibarra et al., 2009; T. Cohen and K. Zurek, 2009; N. Haba et al., 2010;…) annihilates mainly to leptons, for example by proceeding through axion-like particles below the pion mass.
- Many versions of non-minimal SUSY, NMSSM, BMSSM,… May alleviate tension with lightest Higgs bounds.
- Asymmetric Dark Matter (D. E. Kaplan, M. A. Luty, and K. M. Zurek, 2009; A. Fitzpatrick, D. Hooper, and K. M. Zurek, 2010; M.T. Frandsen and S. Sarkar, 2010; S. Chang and L. Goodenough, 2011; M. L. Graesser, I. M. Shoemaker, and L. Vecchi, 2011, S. Profumo and L. Ubaldi, 2011; …) may give a relation between the baryon asymmetry and the DM density, if DM particle is in the few GeV to 10 GeV range
- Emergent DM (Y. Cui, L. Randall and B. Shuve, 2001), a version of asymmetric DM with larger possible parameter range, such as mass up to 100 GeV.
- …

WIMPs are arguably the leading candidates for Dark Matter, due to lack of fine-tuning to get correct relic density. In most models, the annihilation cross section which sets the relic density also implies observable rates in various DM detection experiments.

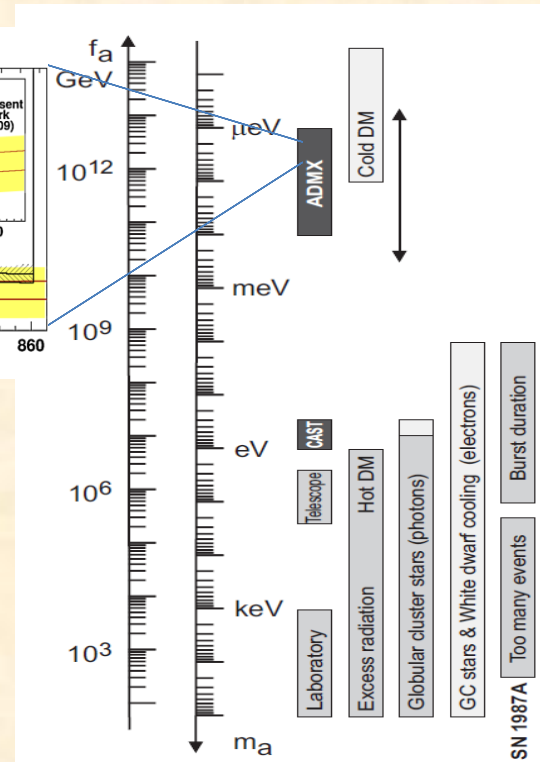
Caution: There are many non-WIMP models that also have good particle physics motivation, and may be detectable, like

- Axions
- Gravitinos
- "SuperWIMPS"
- Non-thermal DM
- Decaying DM
- Sterile Neutrinos
- Q-balls
- … etc

(see, e.g., 700-page *Particle Dark Matter*, Cambridge Univerity Press, 2010, G. Bertone, *ed.*)



S. J. Asztalos & al., PRL 2010, *SQUID-Based Microwave Cavity Search for Dark-Matter Axions*



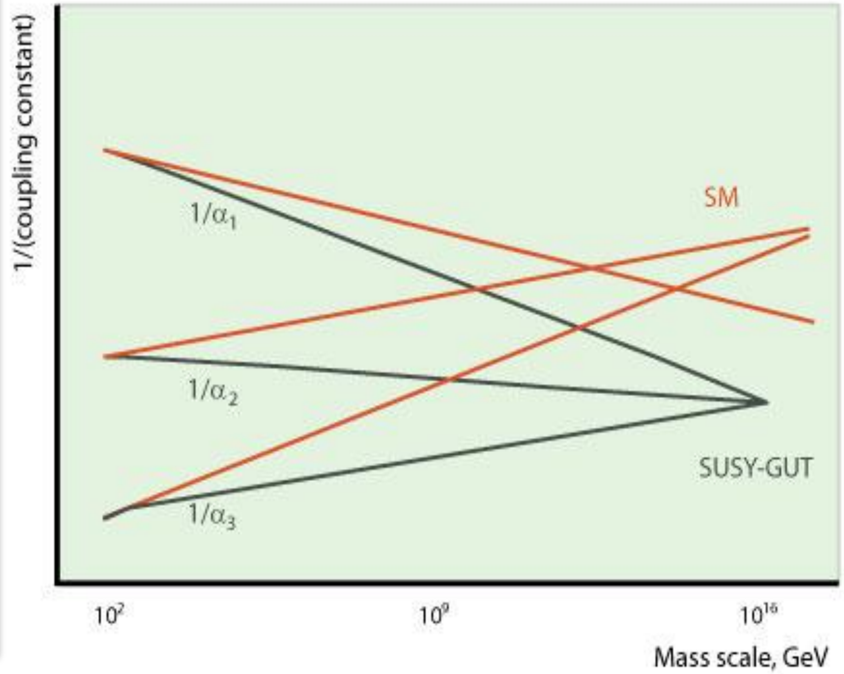
Axions, G. Raffelt, 2006

However, this talk will deal mainly with our main template - SUSY WIMPs

Supersymmetry

- Invented in the 1970's
- Necessary in most string theories
- Restores unification of couplings
- Solves the hierarchy problem
- Can give right scale for neutrino masses
- Predicts in the simplest models (MSSM) a light Higgs (< 130 GeV)
- May (soon?) be detected at LHC
- Gives an excellent dark matter candidate (If R-parity is conserved ⇒ stable on cosmological timescales; needed for proton stability)
- Useful as a template for generic WIMP

Freely available software package, written by P. Gondolo, J. Edsjö, L. B., P. Ullio, M. Schelke, E. Baltz, T. Bringmann and G. Duda.
http://www.darksusy.org



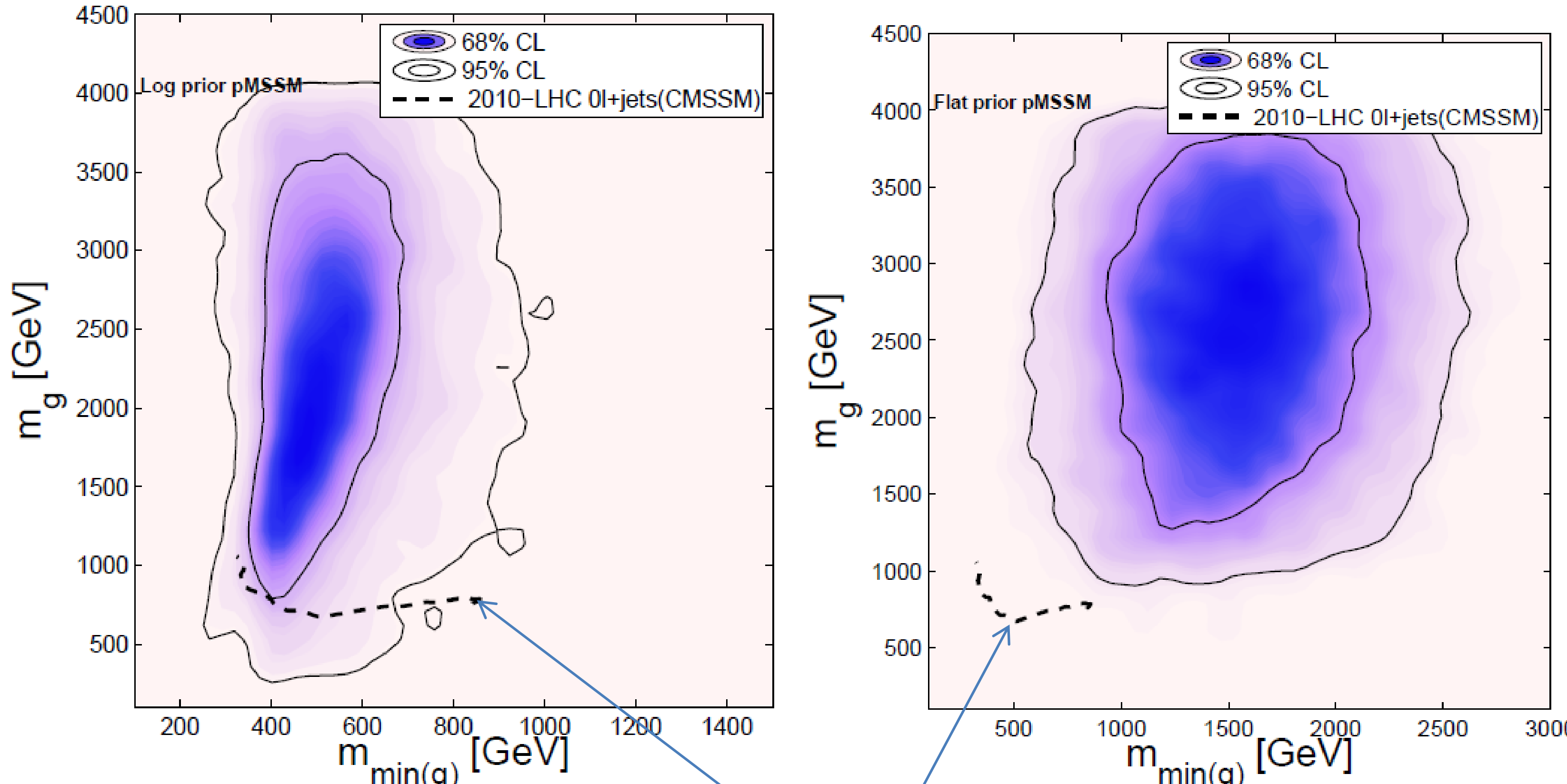
The lightest neutralino: The most natural SUSY dark matter candidate

$$\tilde{\chi}^0 = a_1\tilde{\gamma} + a_2\tilde{Z}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

Gaugino part Higgsino part

Due to requirement of supersymmetry, the neutralino is a Majorana fermion, i.e., its own antiparticle

SUSY at LHC?:
CMSSM and mSUGRA are indeed having trouble (see talks of ATLAS and CMS at this conference), but see, e.g., this 25-parameter phenomenological MSSM (pMSSM).
S.S. AbdusSalam, 2011 (1106.2317), multinest global fit:

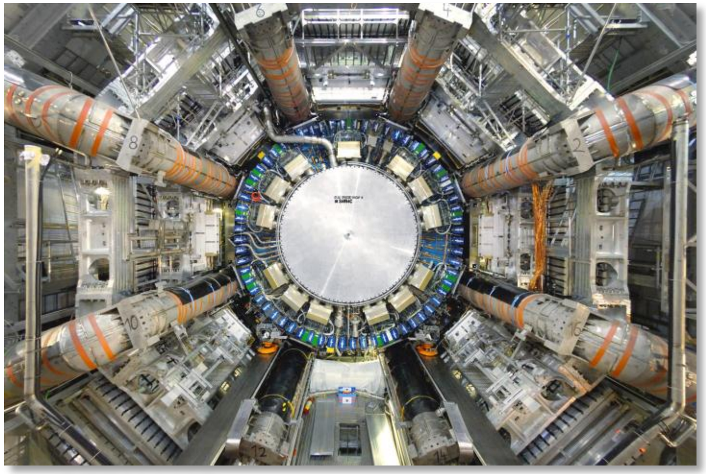


LHC 2010 95% CMSSM limits (but not necessarily so for pMSSM)

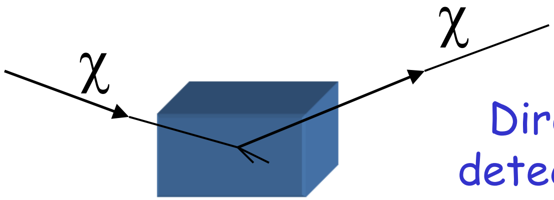
SUSY breaking is little understood; CMSSM and mSUGRA may not be natural models for SUSY breaking, pMSSM is more general.

Methods of WIMP Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…), if kinematically allowed.
- Direct detection of halo dark matter particles in terrestrial detectors.
- Indirect detection of particles produced in dark matter annihilation: neutrinos, gamma rays & other e.m. waves, antiprotons, antideuterons, positrons in ground- or space-based experiments.
- Other possible effects on, e.g., Big Bang Nucleosynthesis, the CMBR, stellar evolution ("dark stars"), reionization of the universe,….
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two different methods.



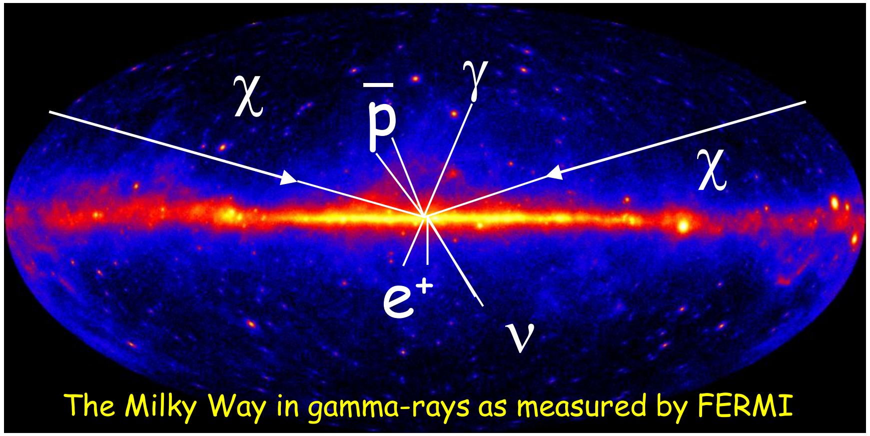
CERN LHC



Direct detection

$$\frac{d\sigma_{si}}{dq} = \frac{1}{\pi v^2}\left(Zf_p + (A-Z)f_n\right)^2 F_A(q) \propto A^2$$

Indirect detection

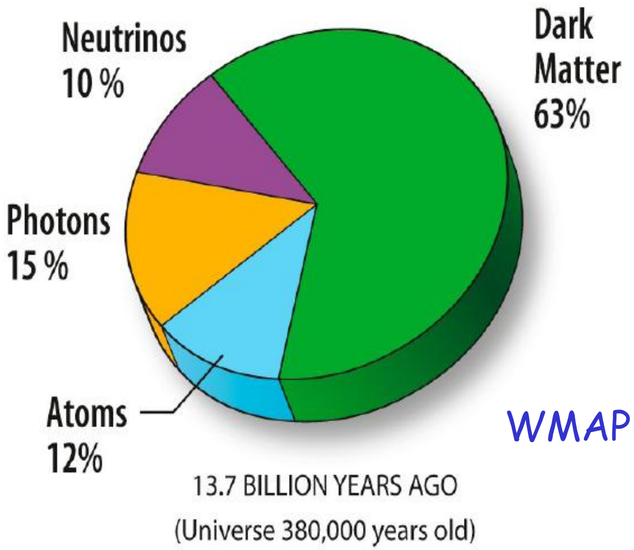


The Milky Way in gamma-rays as measured by FERMI

$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos, also for larger systems like galaxy clusters, cosmological structure.

Since 1998 (Super-K), we know that non-baryonic WIMP dark matter exists! $\Delta m_\nu \neq 0 \Rightarrow m_\nu \neq 0$ (weakly interacting, massive $\Rightarrow$ WIMP!)
WMAP (J. Dunkley et al., 2008): Direct evidence for neutrinos contributing to the energy density at the epoch of the CMBR (380 000 years after the big bang):



WMAP

However, SM neutrinos are not Cold Dark Matter (but rather Hot Dark Matter) and are severely constrained (at present, 10% of DM at most, probably much less)

- Liouville theorem $\Rightarrow$ cannot clump in dwarf halos (Gunn & Tremaine, 1979)
- CMB + Galaxy distribution $\Rightarrow$ limit on sum of ν masses (Bond & Szalay, 1983)

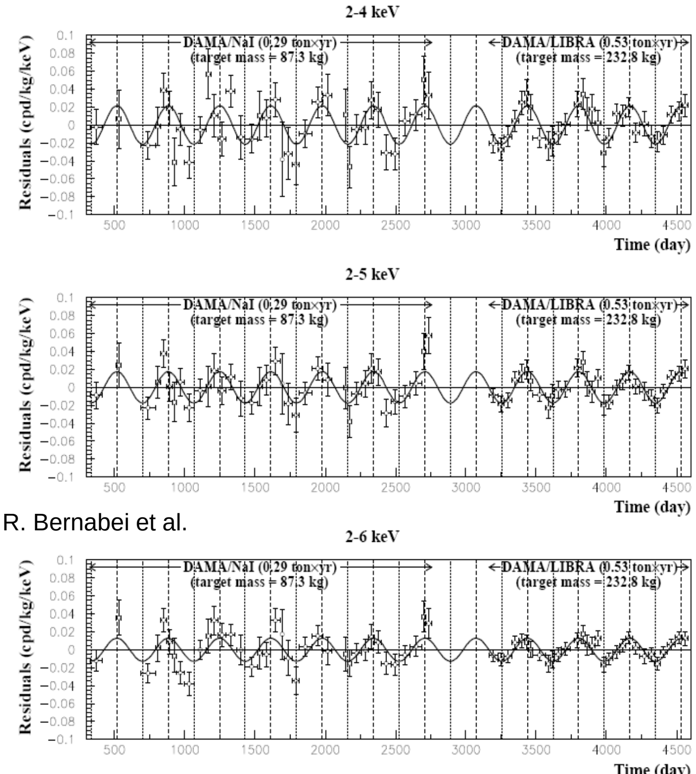
WMAP 2010: $\Sigma\, m_\nu < 1.3$ eV, using CMB data only, for flat, Λ-dominated universe. Adding other astrophysical data (SNe, HST, Ly-a, SDSS,..) one gets a limit down to ~ 0.3 – 0.4 eV (see E. Komatsu & al., 2010, and references therein).

$$\Omega_\nu h^2 = \frac{\sum_\nu m_\nu}{93\, eV}$$, so the upper limit for Ω_ν is between 0.6 % and 3 % (cf Ω_{DM} ~ 25 %).

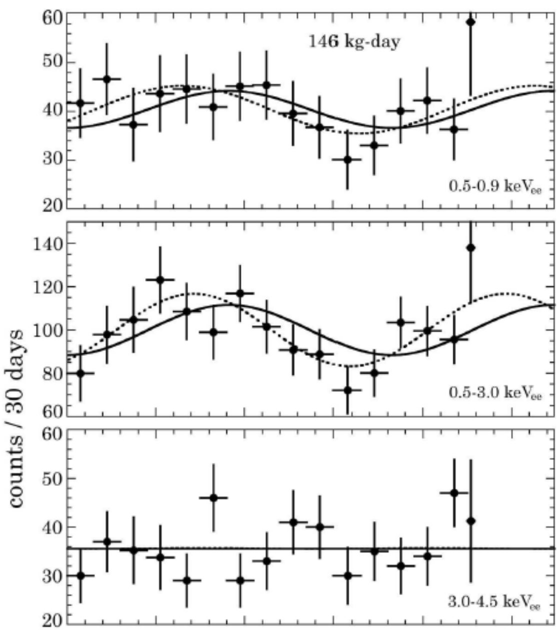
Note: there may be some evidence for sterile neutrinos from cosmological data (J. Hamann & al, 2010; however, this may be due to statistical bias, A.X. Gonzalez-Morales, R. Poltis, B.D. Sherwin and L. Verde, 2011).

What is the main component of dark matter then? Is it given by WIMPs, or even SUSY WIMPs? Nobody knows yet…
There have been many (false?) alarms during the last decade. Most of these phenomena would need contrived (non-WIMP) models for a dark matter explanation:

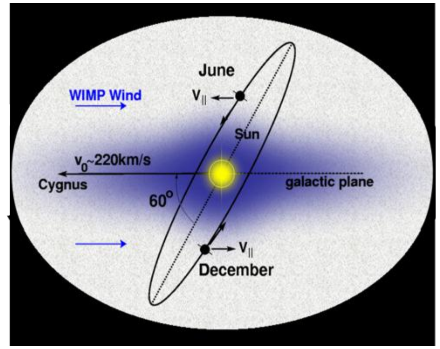
Indication	Status
DAMA annual modulation	Unexplained at the moment – not confirmed by other experiments
EGRET excess of GeV photons	Due to instrument error (?) - not confirmed by FERMI
INTEGRAL 511 keV γ-line from galactic centre	Does not seem to have spherical symmetry - shows an asymmetry which follows the disk (?)
PAMELA: Anomalous ratio e^+/e^-	May be due to DM, or pulsars - energy signature not unique for DM
FERMI positrons + electrons	May be due to DM, or pulsars - energy signature not unique for DM
FERMI excess towards g.c.	Unexplained at the moment – very messy astrophysics
CoGeNT excess events	Tension with other data



R. Bernabei et al.



J. Collar et al.

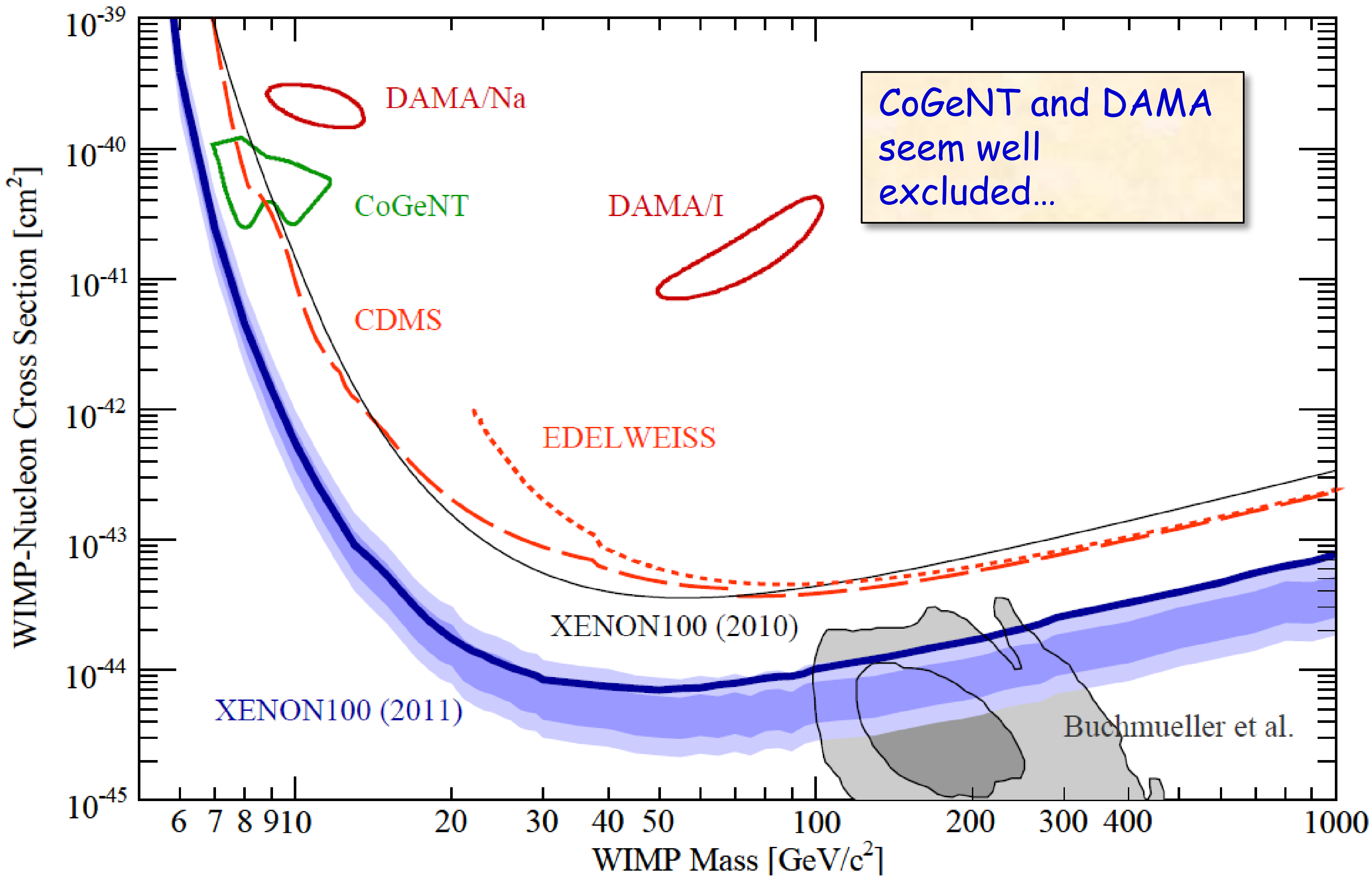


Drukier, Freese, Spergel, 1986

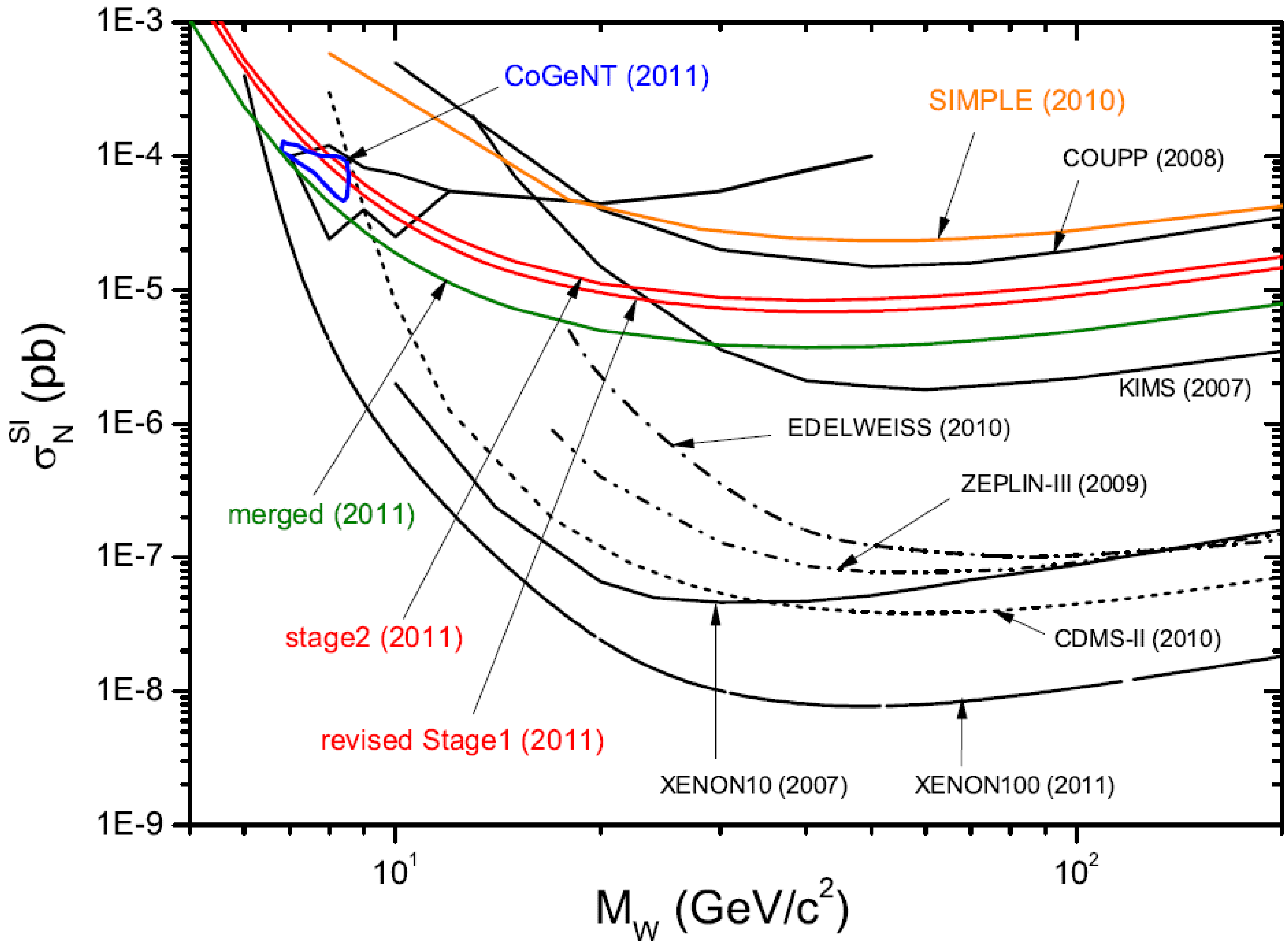
DAMA/LIBRA: Annual modulation of unknown cause. Seen for more than 10 years. Consistent with dark matter signal (but not confirmed by other experiments). Claimed significance: More than 8σ !
What is it? Does not fit in standard WIMP scenario.

Weak (2.8σ) annual modulation signal (?) claimed by CoGeNT experiment, 2011. Does not peak in early June as expected by DM models (mid-April is best fit; D. Hooper and C. Kelso, 1106.1066). Other problems: Modulation amplitude not compatible with CoGeNT unmodulated rate; also excluded by CDMS, XENON100, and SIMPLE.
Thus, CoGeNT modulation is probably not due to dark matter scattering (even including effects of isospin violation, inelastic scattering, non-standard halo,…): T. Schwetz and J. Zupan, 1106.6241; P.J. Fox, J. Kopp, M. Lisanti & N. Weiner, 1107.0717; M. Farina, D. Pappadopulo, A. Strumia & T. Volansky, arXiv:1107.0715, C. McCabe, 1107.0741.
This is a hot and controversial topic in the field of DM detection at the moment!

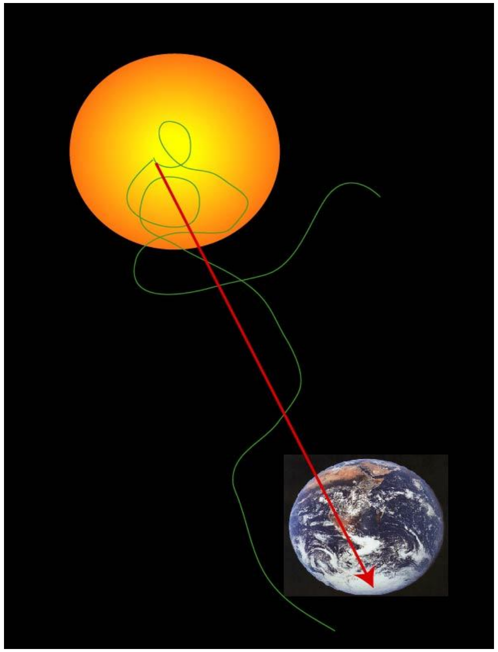
Direct detection limits, Xenon100 new data (with new calibration of low-recoil sensitivity), 2011:



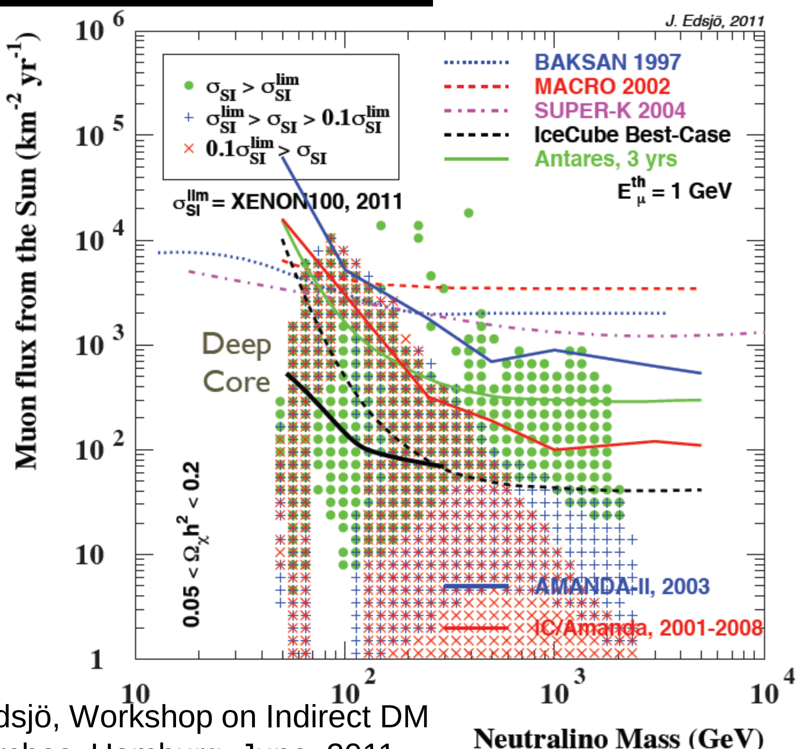
CoGeNT and DAMA seem well excluded…



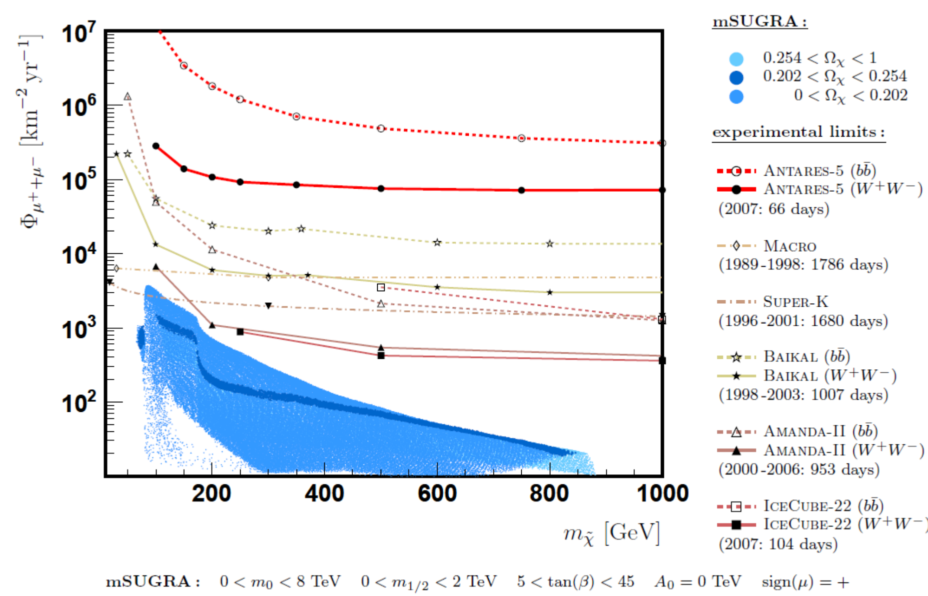
New: 0.2 kg superheated droplet experiment, SIMPLE Collaboration, M. Felizardo & al., arXiv:1106.3014 adds more trouble to CoGeNT (and DAMA…)



Neutrinos from annihilation in the Earth: Not competitive with spin-independent direct detection searches (due to spin-0 elements only in the Earth).
Neutrinos from the Sun: Competitive, due to high proton content of the Sun ⇒ sensitive to spin-dependent interactions. With full IceCube-80 and DeepCore-6 inset operational now, a large new region will be probed. The Mediterranean detector ANTARES has just started to produce limits. (Might be expanded to a km^3 array – KM3NET?)



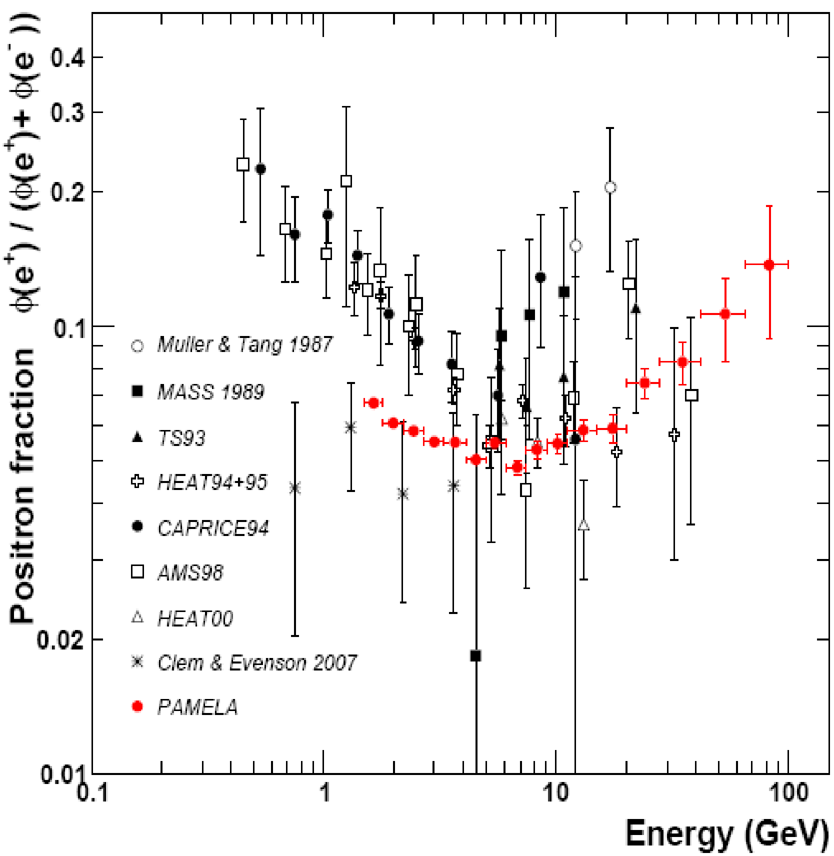
J. Edsjö, Workshop on Indirect DM Searches, Hamburg, June, 2011

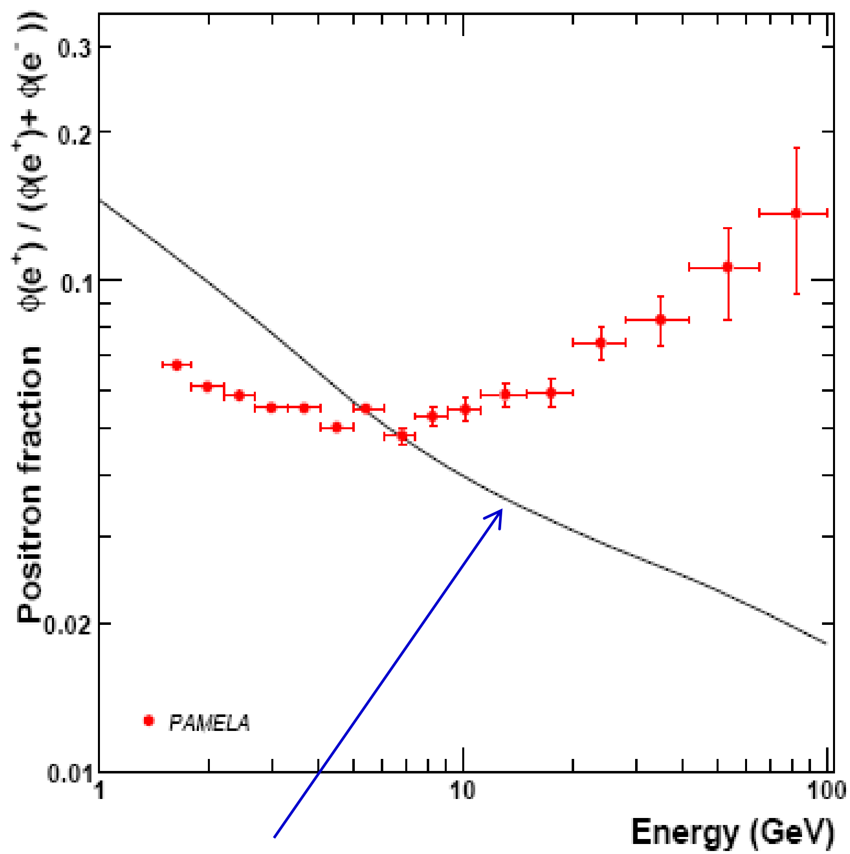


G. Lim (ANTARES), PhD thesis, NIKHEF, 2011

Antimatter in the cosmic rays:
The visible universe consists only of matter. DM annihilation gives equal numbers of particles and antiparticles. Secondary production of antiparticles from cosmic rays is small $\Rightarrow$ Antimatter may be a good indicator of DM annihilation.

The surprising PAMELA data on the positron ratio up to 100 GeV. (O. Adriani et al., Nature, 2009) A very important result (see A. Strumia, EPS-HEP, Krakow, 2009):

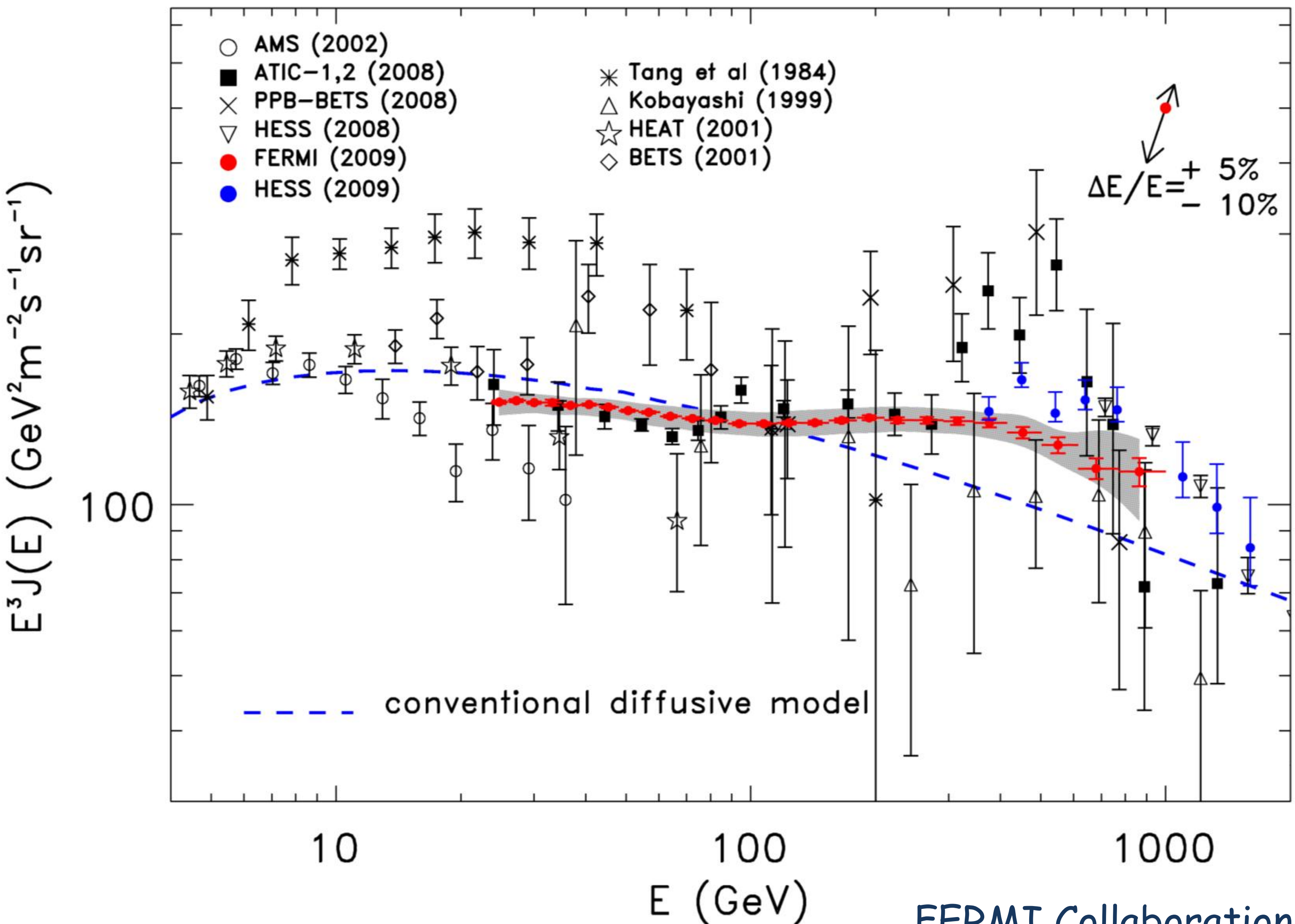




Prediction from secondary production by cosmic rays:
Moskalenko & Strong, 1998
(*cf.* R. Trotta & al., 2010)

A surprise also from FERMI

Sum of electron and positron flux versus energy:



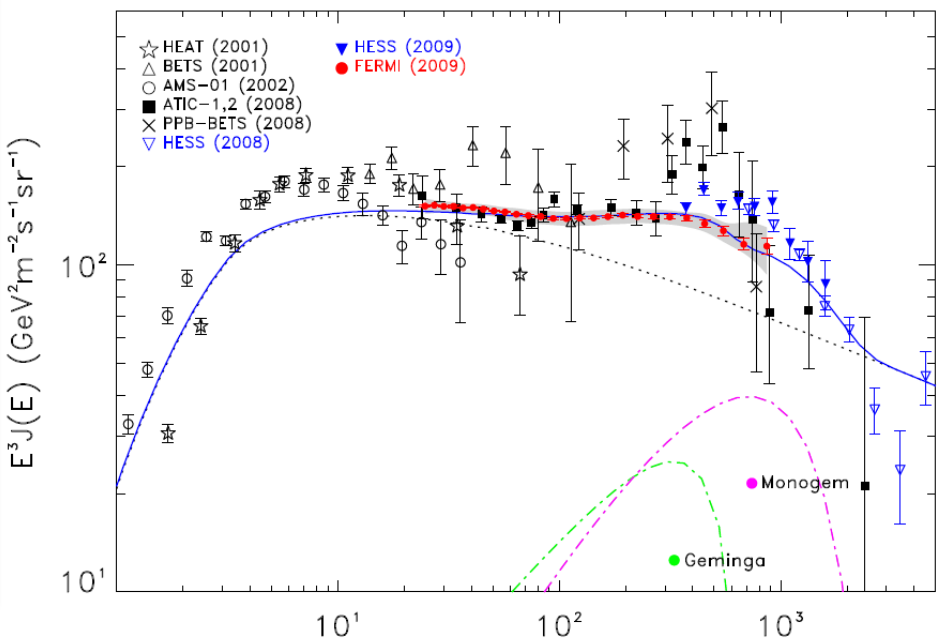
FERMI Collaboration, A.A. Abdo & al, PRL 2009.

The rising positron ratio and the "bump" in the electron plus positron spectrum are impossible to explain using only secondary production in cosmic rays. A new primary source of positrons is needed. Two main possibilities have been explored:

1. Pulsars (or other supernova remnants)
2. Dark Matter

For both scenarios, the absence of an excesss of antiprotons (PAMELA, 2009) places stringent bounds ("leptophilic" processes must dominate for dark matter)

1. Positrons generated by a class of extreme objects: supernova remnants (pulsars):

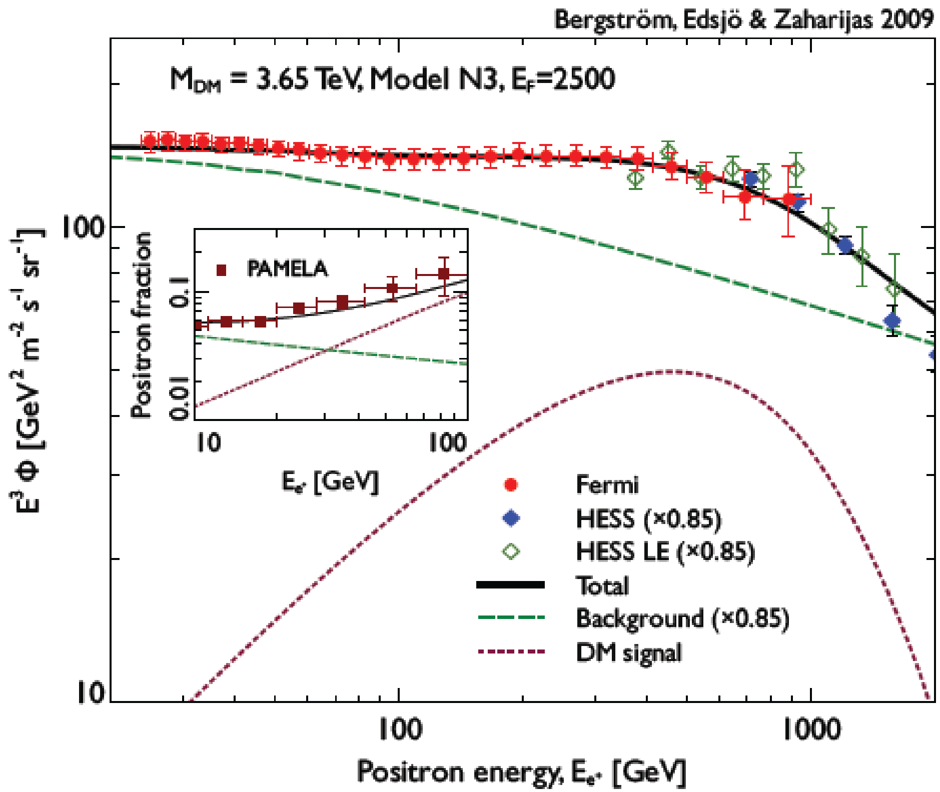


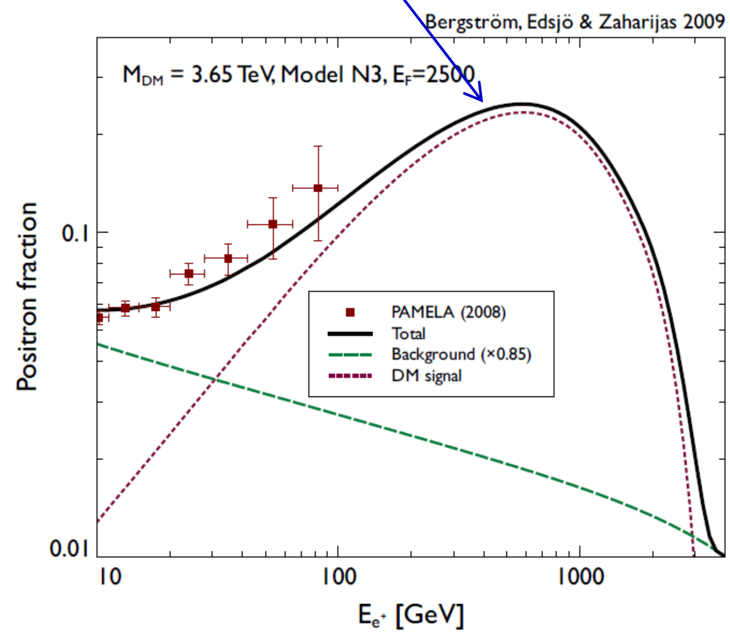
D. Grasso et al., 2009

For pulsars, the fluxes are essentially unconstrained and can be adjusted to fit. Anisotropy expected, but below a percent $\Rightarrow$ undetectable at present.

2. Dark Matter fit

The energy dependence will be checked by AMS-02 (successfully launched to the International Space in May, 2011). However, non-DM models may give similar distribution.





The shape and normalization can be explained, but at a high price: Only annihilation to leptons, and large "boost factor" needed. Models can be constructed based, e.g., on Sommerfeld enhancement (e.g., M. Cirelli & al., 2008, N. Arkani-Hamed & al., 2009; D. Finkbeiner, & al, 2011), but live dangerously close to being ruled out by other measurements (G. Bertone, & al.,2009; L.B., J. Edsjö and G. Zaharijas, PRL 2009; P. Meade & al., 2009, and many others). Diffusion removes all directional and much of the spectral information for both DM candidates and pulsar sources. Since 2009 (see A. Strumia, EPS-HEP Krakow), this possible hint of dark matter has become much colder – though not yet ruled out…

Indirect detection of WIMPs through γ-rays

Three types of signal:

• Continuous from π^0, K^0, … decays.

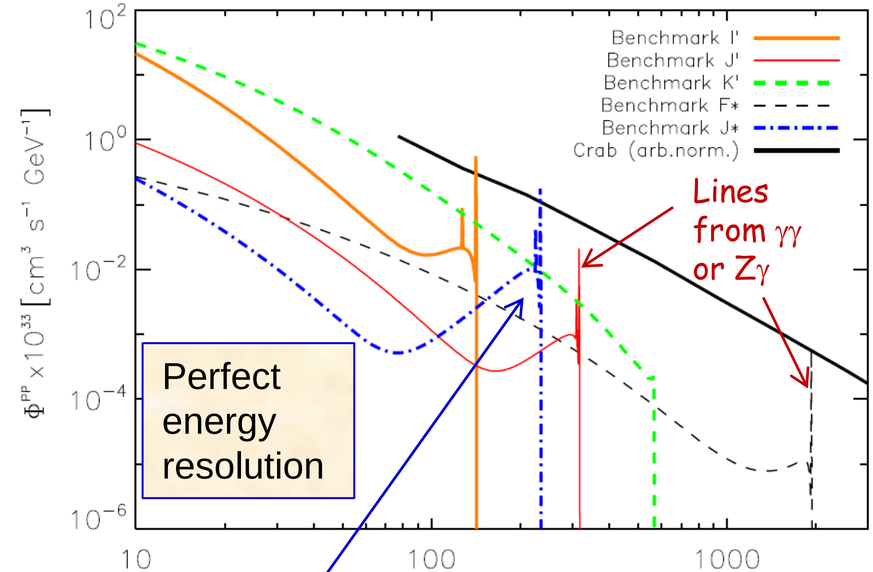
• Monoenergetic line from quantum loop effects, $\chi\chi \rightarrow \gamma\gamma$ and $Z\gamma$. "Smoking gun"

• Internal bremsstrahlung from QED process – may give orders of magnitude enhancement, and a conspicuous peak at high gamma-ray energy for Majorana particles (L.B.,1989; T. Bringmann, L.B. & J. Edsjö, 2008; M. Ciafalone & al., 2011; N. F. Bell & al., 2011)

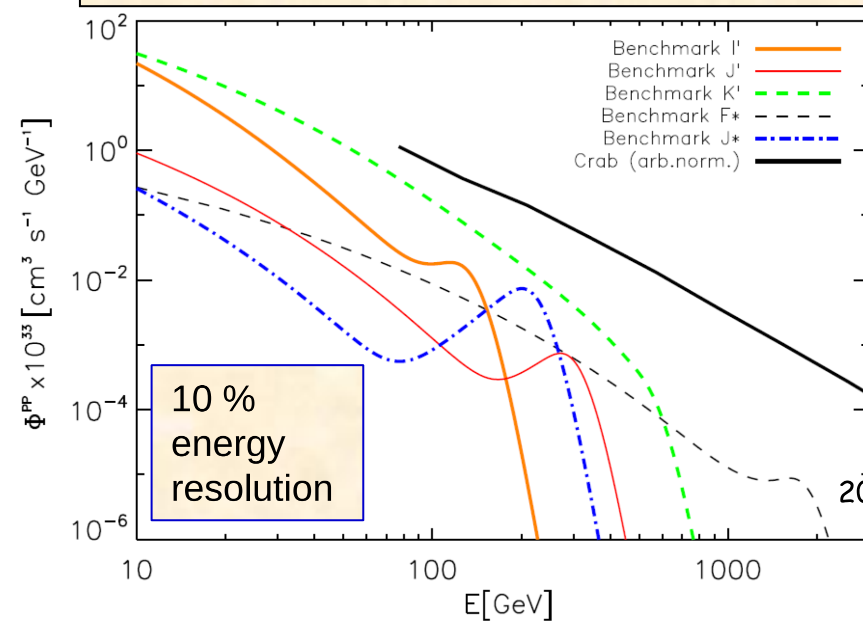
Enhanced flux possible thanks to halo density profile and substructure (as predicted by N-body simulations of CDM).

Good spectral and angular signatures! (See T. Bringmann & al., 2011)

But uncertainties in the predictions of absolute rates, due e.g. to poorly known DM density profile.



Important contribution for SUSY DM : Internal bremsstrahlung (T. Bringmann, L.B., J. Edsjö, 2007)



T. Bringmann, M. Doro & M. Fornasa, 2008; cf. L.B., P.Ullio & J. Buckley 1998.

One major uncertainty for indirect detection, especially of gamma-rays: The halo dark matter density distribution at small scales is virtually unknown. Gamma-ray rates towards the Galactic Center may vary by factor of 1000 or more. However, much less variation (about a factor 2 – 10) for objects (such as dwarf galaxies) contained in the angular resolution cone, and even less for galaxy clusters.

Fits to N-body simulations

$$\rho_{\text{Einasto}}(r) = \rho_s e^{\left(-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^{\alpha} - 1\right]\right)}, \ \alpha \approx 0.17$$

$$\rho_{\text{NFW}}(r) = \frac{c}{r(a+r)^2};$$

Fits to rotation curves

$$\rho_{\text{Burkert}}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

$$\rho_{\text{Isothermal}}(r) = \frac{c}{a^2+r^2};$$

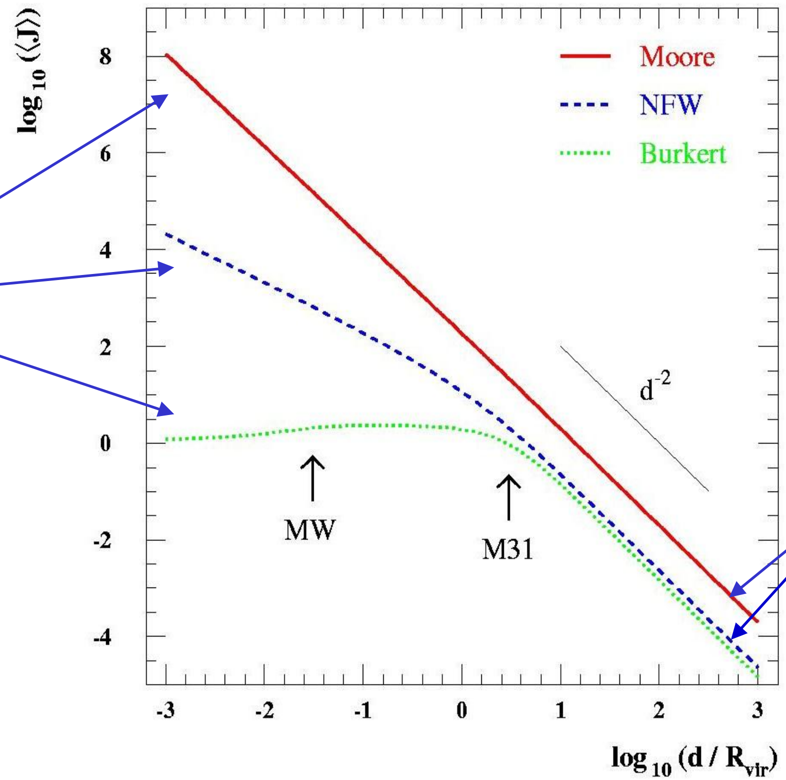
At the solar position, the local density is around 0.39 ± 0.03 GeV/cm^3 (R. Catena & P. Ullio, 2010)

DM Indirect Detection rate = (Particle)×(Astro).

~ <σv> ~ J

$$\bar{J}(\hat{n};\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int d\Omega \int \frac{dl}{(8.5\,kpc)}\left(\frac{\rho(\vec{r})}{0.3\,GeV/cm^3}\right)^2$$

Note large uncertainty of flux for nearby objects (Milky Way center, LMC)



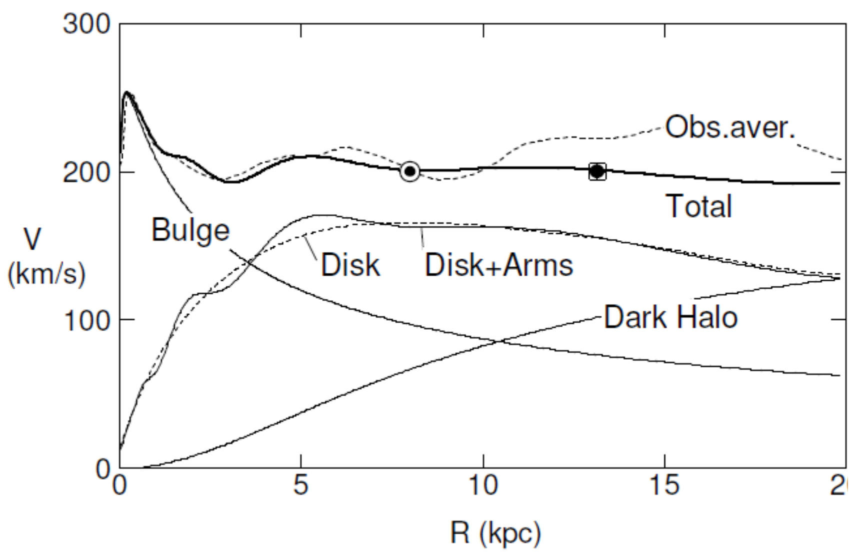
In this region (for cosmological distances), the uncertainty is much smaller

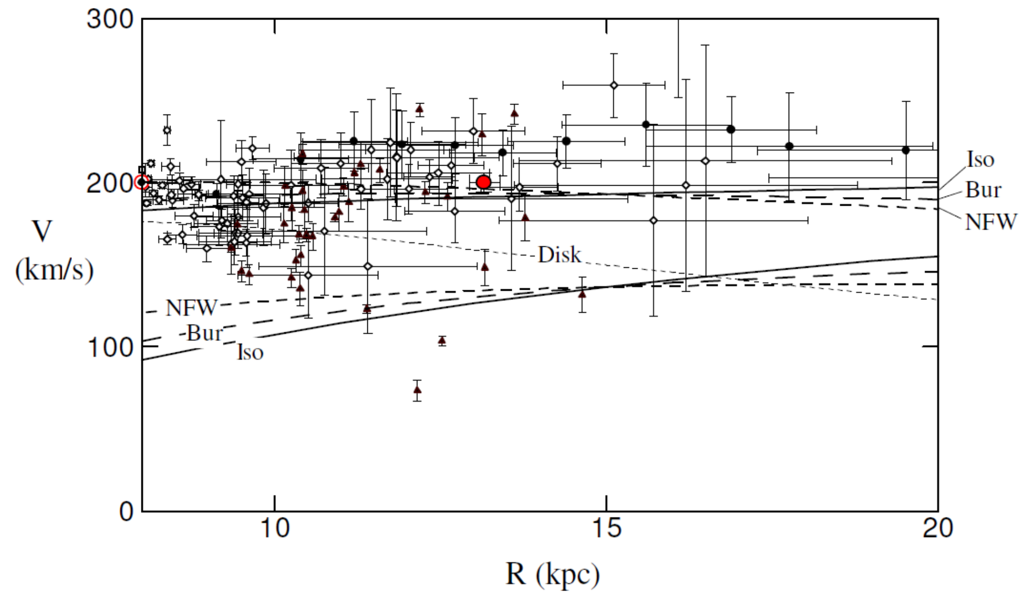
P. Ullio, L.B., J. Edsjö, 2002

FIG. 4: Scaling of the collected γ-ray flux with the distance d between the detector and the center of a halo, for three different halo profiles. The angular acceptance of the detector is assumed to be $\Delta\Omega = 10^{-3}$sr. The plot is for a $10^{12} M_\odot$ halo, the arrows indicate the position on the horizontal axis for the Milky Way and Andromeda; the case for other masses is analogous.

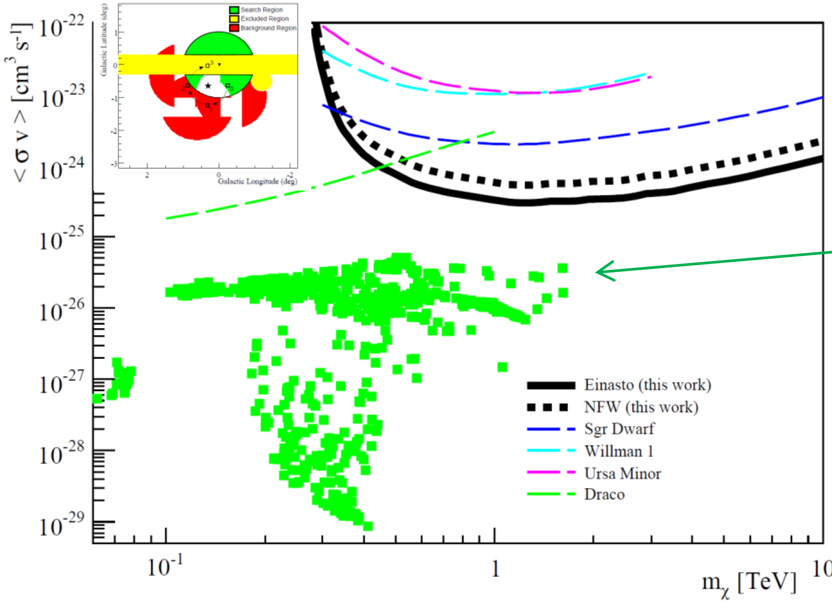
Can't we determine right halo model from the Milky Way rotation curve?

No, unfortunately not:





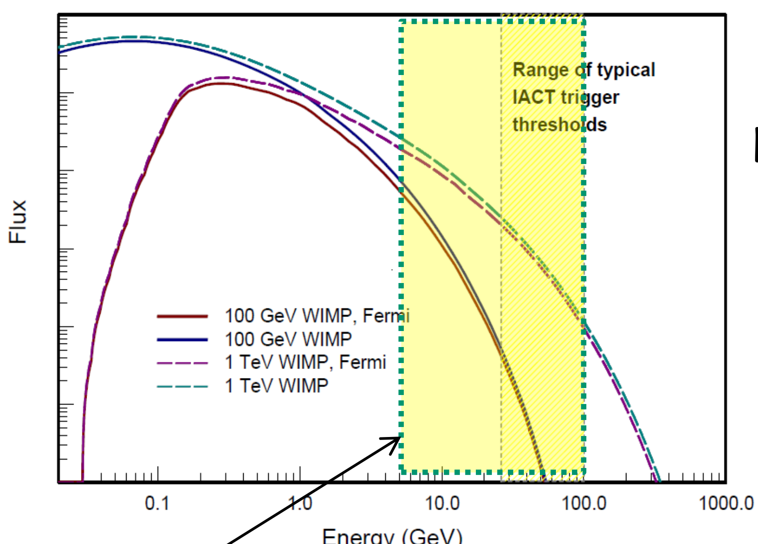
Y. Sofue, M. Honma & T. Omodaka, 2008



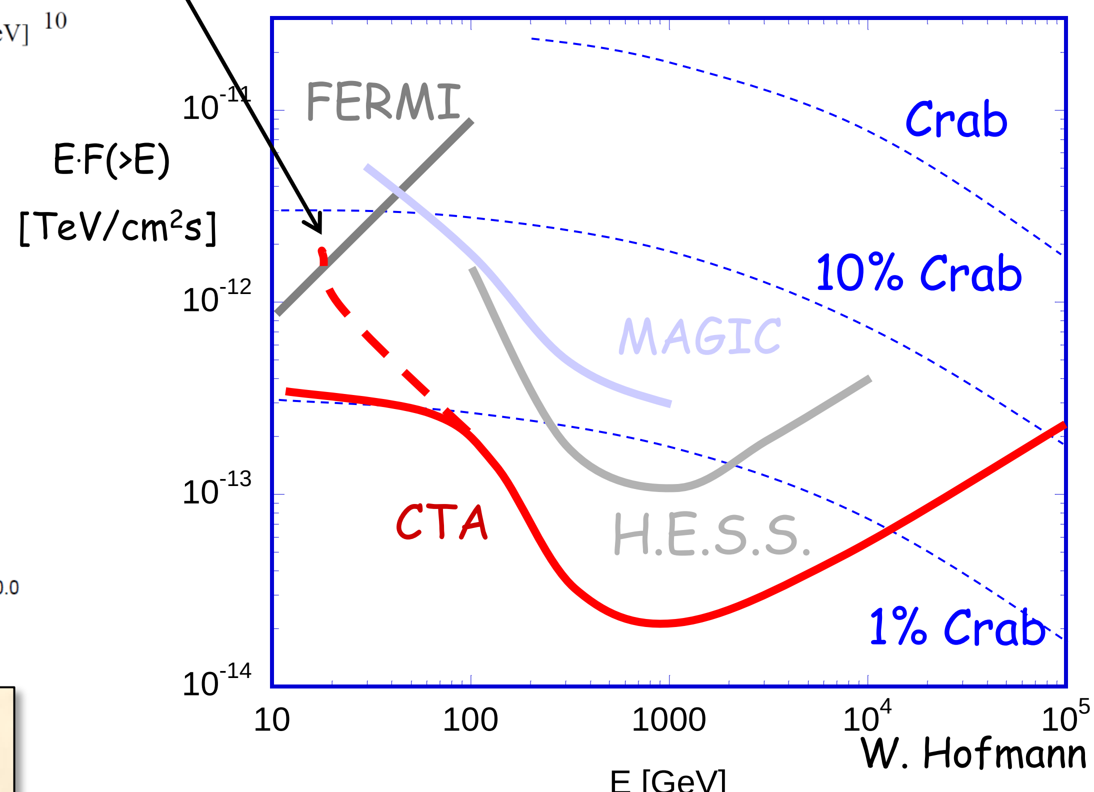
Present best limits towards the galactic centre, and towards dwarf galaxies from ground-based experiments (HESS, March 2011)

WMAP-compatible SUSY models

Maybe with CTA (Cherenkov Telescope Array – data taking 2018?) one can reach the required sensitivity. However, it seems that the energy threshold may be too high (30 GeV).



T.A. Porter, R.P. Johnson and P.W. Graham, 2011

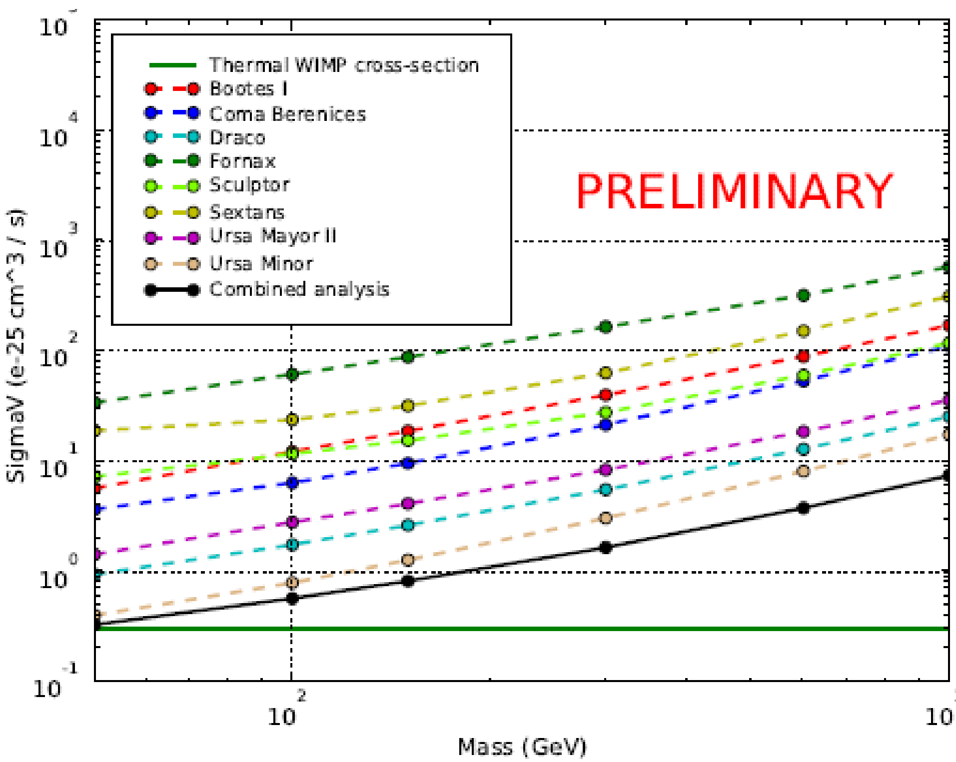


W. Hofmann

Can one get down to this threshold (5 GeV)?
F. Aharonian et al., 2000: Yes, 5@5 - a 5 GeV threshold instrument 5000 m above sea level.

New promising method: Stacking data from many dwarf galaxies, FERMI Collaboration (preliminary), 2011

Fermi Collaboration, M.L. Garde et al., 2011

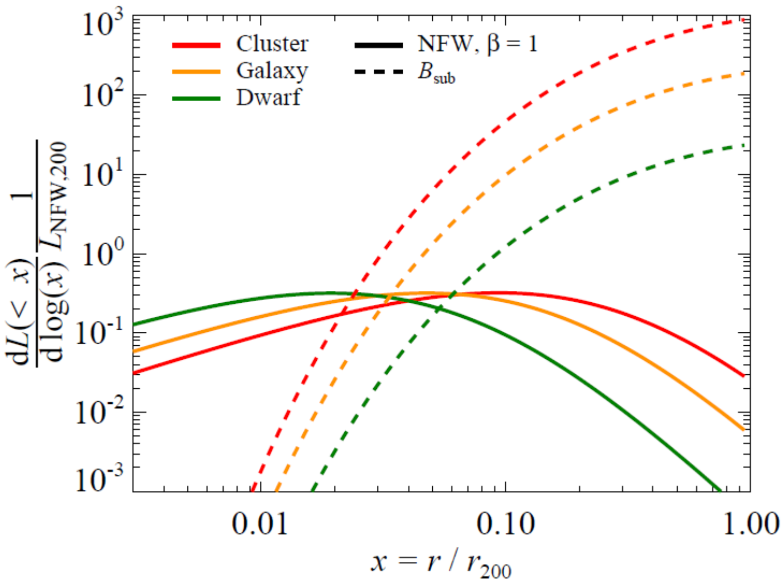


By stacking the data, sensitivity to the J-factor may also be minimized

"Canonical" WIMP cross section

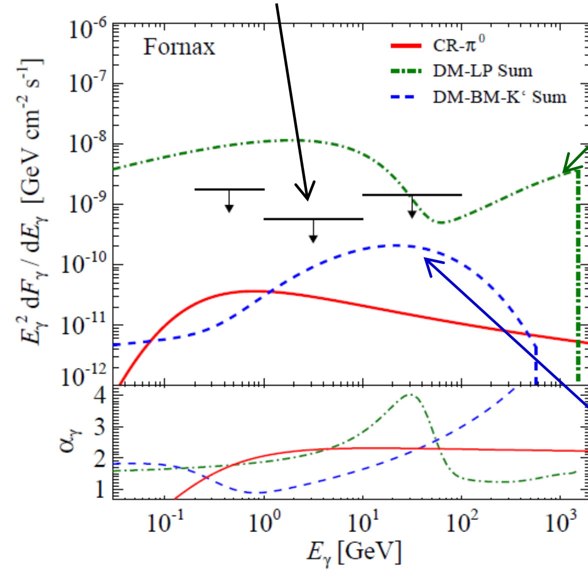
Figure 1: Upper limits on WIMP annihilation cross section for annihilation into 100% $b\bar{b}$, σv evaluated at m_{WIMP} = 50, 100, 150, 300, 600 and 1000 GeV. The expected thermal WIMP cross-section is plotted as a reference. The limits are 84% two-sided.

Recent development: Galaxy clusters – where a DM signal may first be found? (Fritz Zwicky would be pleased…)



A. Pinzke, C. Pfrommer and L.B., 2011 (1105.3240).

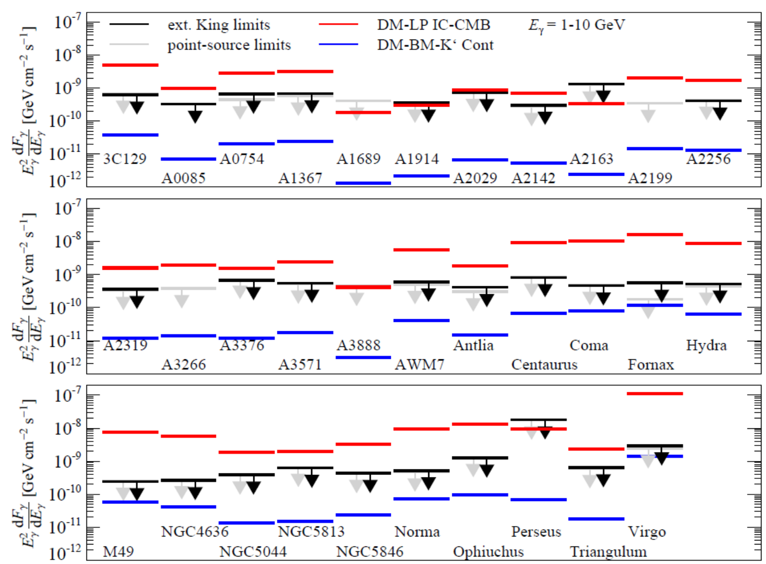
Ferimi-LAT spatially extended limit



Leptophilic model normalized to PAMELA/FERMI flux (already excluded)

Cosmic ray-induced flux

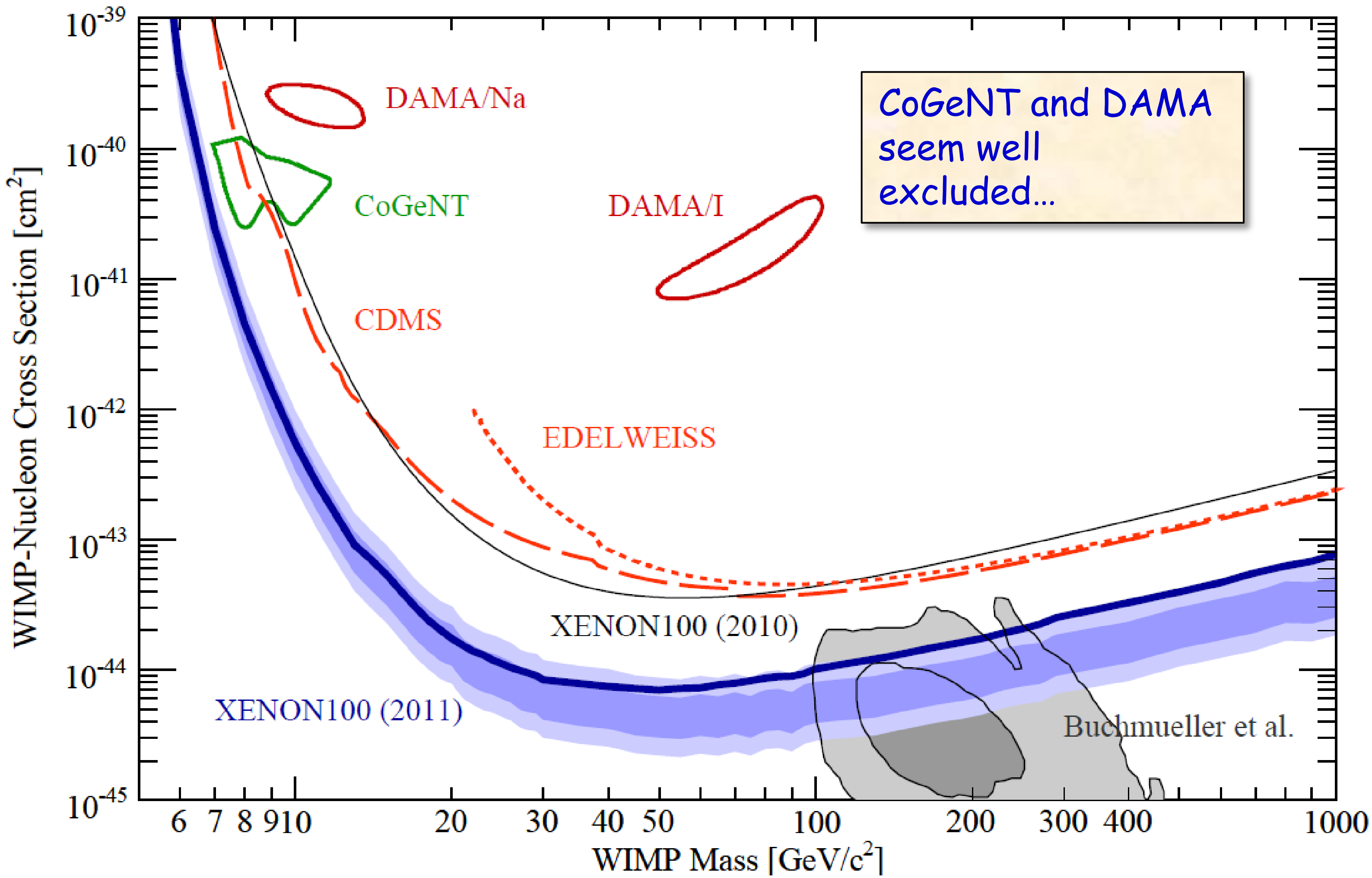
Benchmark model for pMSSM



Tidal effects are smaller for clusters ⇒ boost factor of the order of 1000 possible (without Sommerfeld enhancement!). See also M.A. Sanchez-Conde, M. Cannoni, F. Zandanel, Mario E. Gomez and F. Prada 2011 (1104.3530); L. Gao, C.S. Frenk, A. Jenkins, V. Springel and S.D.M. White, 2011 (1107.1916).

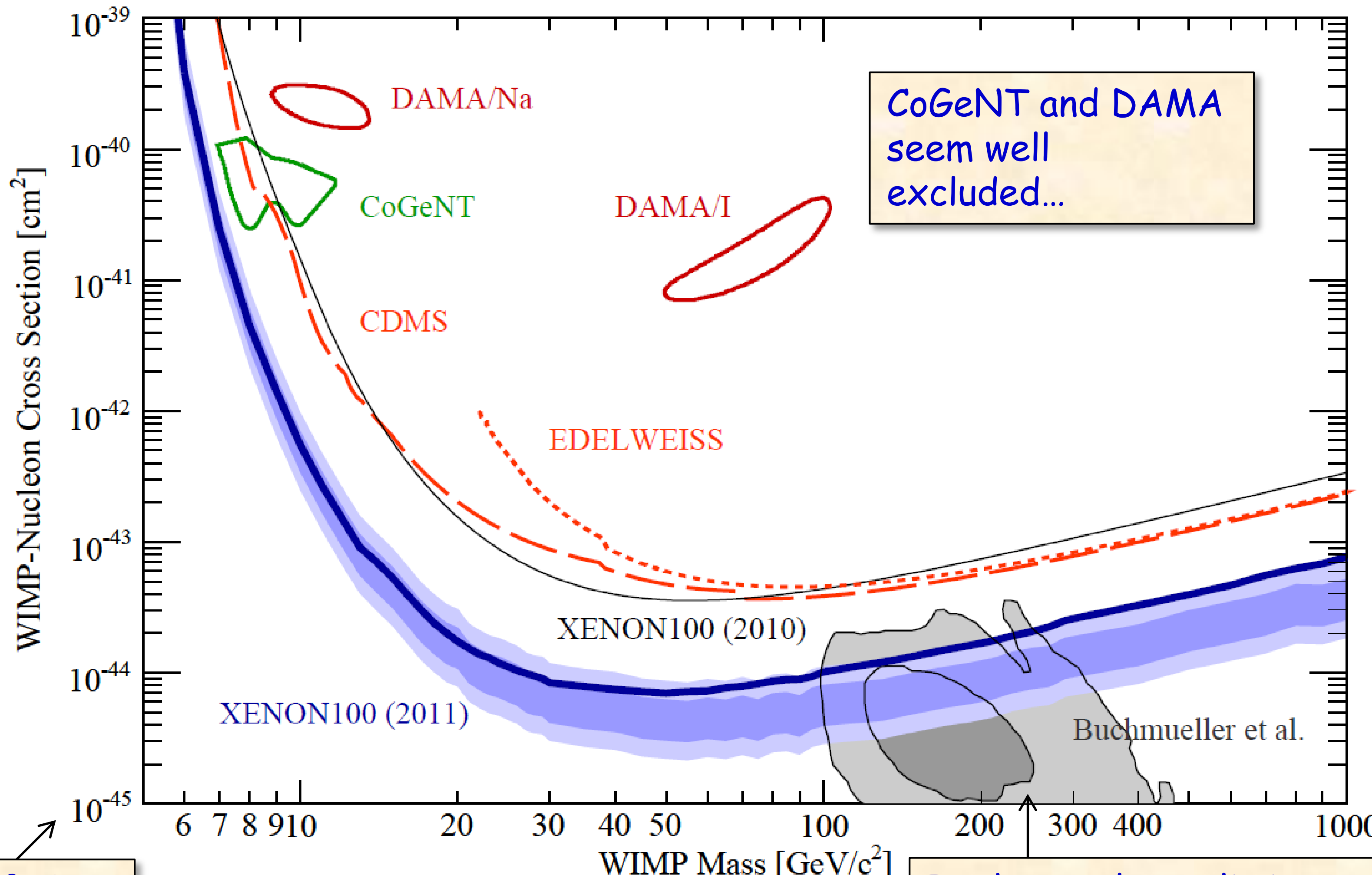
Predicted signal/noise is roughly a factor of 10 better for clusters than for dwarf galaxies! Clusters may also be suitable for stacking of FERMI data.

Direct detection limits, Xenon100 new data (with new calibration of low-recoil sensitivity), 2011:



CoGeNT and DAMA seem well excluded...

Direct detection limits, Xenon100 new data (with new calibration of low-recoil sensitivity), 2011:

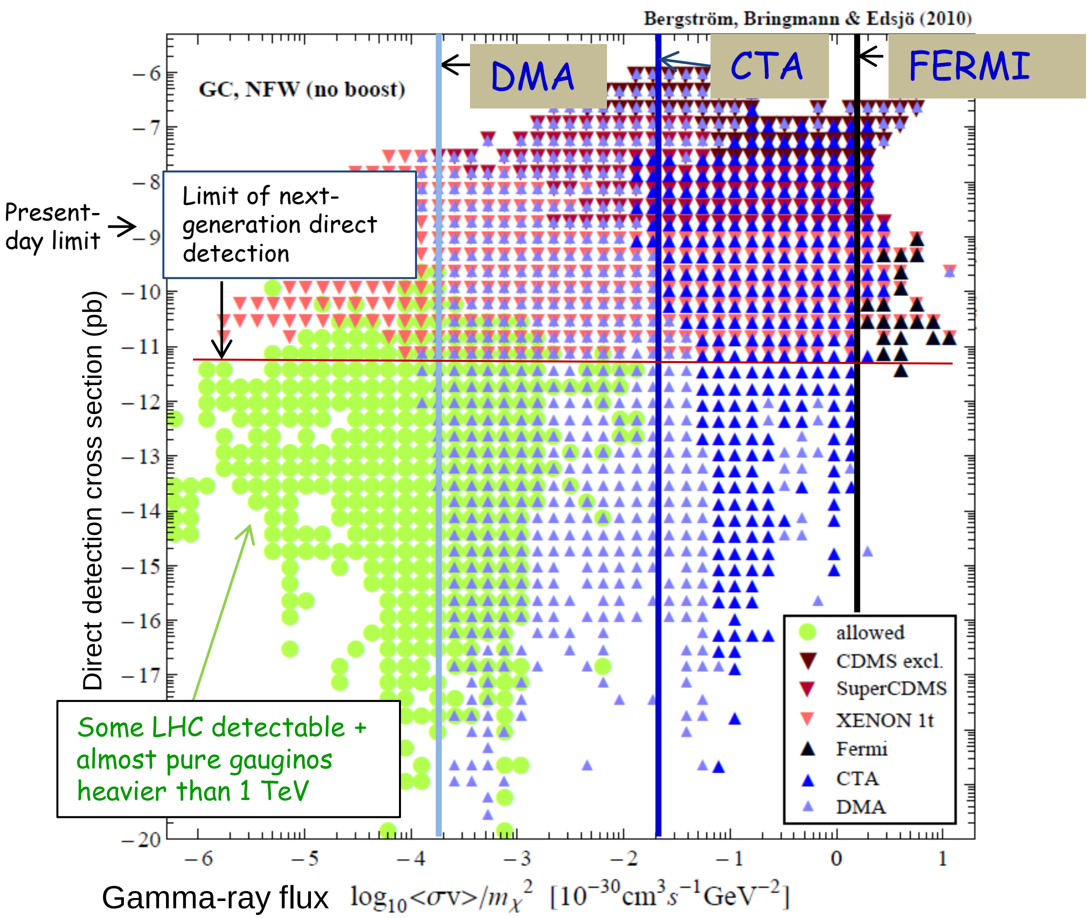


CoGeNT and DAMA seem well excluded...

10^{-9} pb

Is there a lower limit to the SUSY cross section?

What if the DM mass is too high for LHC and/or direct detection? And discovery of a light Higgs (m_H < 130 GeV) still indicates validity of the MSSM? Then DM search in γ-rays may be a window for particle physics beyond the Standard Model!



DMA: Dark Matter Array - a dedicated gamma-ray detector for dark matter?
(T. Bringmann, L.B., J. Edsjö, 2011)

General pMSSM scan, WMAP-compatible relic density. Check if $S/(S+B)^{0.5} > 5$ in the "best" bin (and demand $S > 5$)

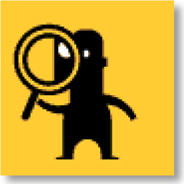
DMA would be a particle physics experiment, cost ~ 1 GEUR. Challenging hard- and software development needed.

Construction time ~ 10 years, with principle tested in 5@5-type detector at 5 km in a few years…

Summary: Where do we stand?

• Dark Matter exists - it is cold, i.e. moved slowly (non-relativistically) when structure formed.
• The relic density may be computed using early-universe thermodynamics.
• The WIMP miracle: For typical weak interaction couplings, and a mass around 100 - 1000 GeV, the relic density comes out right.
• The lightest supersymmetric neutralino of pMSSM is an excellent template for a Dark Matter WIMP.
• Detection will not be easy nor guaranteed, but the three complementary methods: accelerator search, direct and indirect detection, each cover a sizeable fraction of possible WIMP properties.
• There may be hints (however, vague and not at all conclusive) of something already being seen…
• The coming years will be extremely interesting - AMS-02 will check the cosmic-ray positron and antiproton spectra, FERMI will continue collecting gamma-ray data with galaxy clusters as promising targets. MAGIC and HESS-2 will have improved gamma-ray sensitivity, with later on CTA as an important player (and perhaps a dedicated Dark Matter Array?). IceCube/DeepCore will probe ν data from the direction of the Sun. XENON1t will be installed; new technologies develop rapidly (COUPP, SIMPLE, CoGeNT, Super-CDMS, DARWIN, EUREKA,…)
• And, last but not least, CERN:s LHC is now working extremely well!
• Maybe it is still too early to solve the DM puzzle (but welcome to EPS-HEP2013 in Stockholm!). At least we will know much more about what it is not…

The hunt for Dark Matter continues!



The End